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AN UPDATE ON NIF PULSED POWER*

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Abstract

The National Ignition Facility (NIF) is a 192-beam laser fusion driver operating at Lawrence Livermore National Laboratory. NIF relies on three large-scale pulsed power systems to achieve its goals: the Power Conditioning Unit (PCU), which provides flashlamp excitation for the laser's injection system; the Power Conditioning System (PCS), which provides the multi-megajoule pulsed excitation required to drive flashlamps in the laser's optical amplifiers; and the Plasma Electrode Pockels Cell (PEPC), which enables NIF to take advantage of a four-pass main amplifier.

Years of production, installation, and commissioning of the three NIF pulsed power systems are now complete. Seven-day-per-week operation of the laser has commenced, with the three pulsed power systems providing routine support of laser operations. We present the details of the status and operational experience associated with the three systems along with a projection of the future for NIF pulsed power.

I. INTRODUCTION/STATUS

The three pulsed power subsystems of the National Ignition Facility at the Lawrence Livermore National Laboratory, the Power Conditioning System (PCS), the Power Conditioning Unit (PCU) and the Plasma Electrode Pockels Cell (PEPC) are now fully operational, supporting seven-day-per-week laser operations. This represents the culmination of more than a decade of design, development, production, installation and commissioning of 192 PCS modules, 48 PCU modules and 48 PEPCs (employing nearly 300 high-power pulse generators).

The last elements of the pulsed power subsystems were delivered to the facility in early 2008 with installation and commissioning of the hardware continuing into the third quarter of CY2008. Equipment was commissioned on a bundle basis (corresponding to eight beams, the fundamental functional unit of NIF), with each subsystem bundle passing rigorous installation qualification (IQ) and an operations qualification (OQ) before being integrated with all other elements of the bundle to join the operational beamlines of the facility.

Nominal 96-beam shots (corresponding to half of NIF) began in the fall of 2008 and culminated in December with a series of shots employing more than 110 beams.

This was followed by a shot campaign in early 2009 employing all 192 beams. In March 2009, NIF delivered 1.1 MJ of UV light to target chamber center, meeting or exceeding all specified facility completion criteria.

NIF is on a course to begin a fusion shot campaign as early as 2010. As such, the laser system is being exercised on a daily basis (i.e., seven days per week) with operations occurring on the off-shift, and maintenance, system upgrades and offline testing occurring during the day.

II. BRIEF DESCRIPTION OF THE THREE NIF PULSED POWER SUBSYSTEMS

A. Power Conditioning System

The PCS provides the pulsed excitation required to drive the nearly 8000 flashlamps in the NIF large-aperture optical amplifiers: a two-pass power amplifier and a four-pass main amplifier. Each of the 192 modules, housed in four capacitor bays, is capable of storing ~ 2 MJ before delivering that energy in a critically damped 0.5-MA, 400- μ s current pulse to 20 pairs of flashlamps.¹ The main pulse is preceded in time (three hundred microseconds) by a relatively low-power pre-ionization pulse that prepares the xenon gas for the main pulse. Each main discharge is followed by a low-power "lamp check" pulse that verifies the health of the lamps before forced air cooling of the laser begins. Both the main and PILC (pre-ionization/lamp-check) circuits rely on high-pressure gas switches to initiate the lamp discharges. A simplified schematic of a single PCS module is shown in Figure 1. One of four populated capacitor bays is shown in Figure 2.

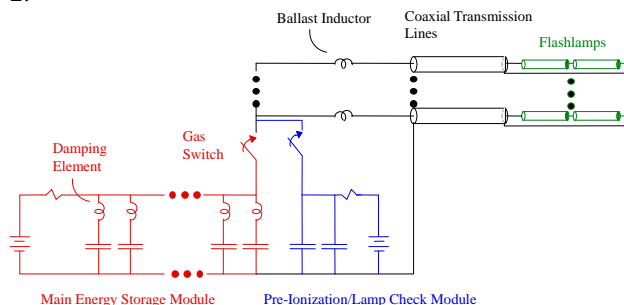


Figure 1. Schematic of a NIF Power Conditioning System module and flashlamp load.

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Figure 2. One of four fully-populated NIF Capacitor Bays.

B. Power Conditioning Unit

The PCU likewise drives flashlamps, though for the comparatively low-power, high-gain front end of the laser. (Each PCU drives six pairs of flashlamps, delivering a nominal 1.25 kJ to each lamp.) Emphasis for a PCU is on extreme reliability, accuracy and repeatability, since the gain of the pre-amplifier of the laser system grossly magnifies any beam-to-beam or shot-to-shot deviations and/or inaccuracies.² Despite their similar missions, the architecture of a PCU is much different from that of the PCS. A PCU incorporates a MOS-controlled thyristor (MCT) and a dual series-injection (1:20) step-up transformer to break down a pair of flashlamps and thus initiate a discharge of the main energy storage capacitor into the lamps. The saturated inductance of one-half of the dual transformer serves as the inductance of a single-stage (LC) pulse-forming network that drives each lamp. A simplified schematic of a single stage of the PCU is illustrated in Figure 3, with an assembly shown in Figure 4.

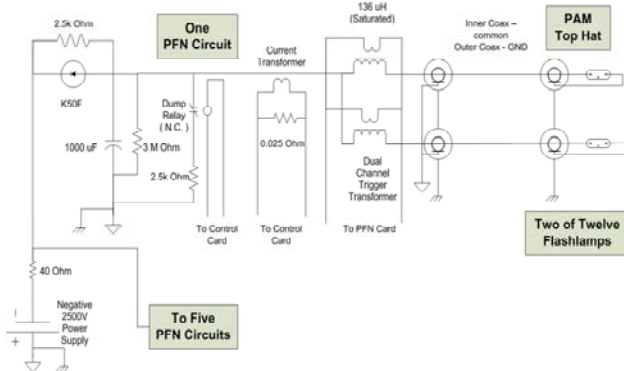


Figure 3. Schematic of a NIF PCU.

C. Plasma Electrode Pockels Cell

The PEPC differs significantly from the other NIF pulsed power systems. As depicted in



Figure 4. Assembled Power Conditioning Unit.

Figure 5, the PEPC is part of an active optical switch that allows beams to be trapped and then released, thus allowing NIF to take advantage of a four-pass main architecture, greatly reducing the cost and size of the laser.³ The operation of PEPC can be understood in the following context: A plasma is initiated in low-pressure helium gas located on both sides of a potassium dihydrogen phosphate (KDP) crystal utilizing a relatively low-voltage, low-current “simmer” pulse. A 2.2-kA capacitive discharge then increases the plasma density to a level such that it mimics a conductor, with the added advantage of being optically transparent. Application of a short duration (three hundred nanosecond) 17-kV pulse allows the KDP to selectively rotate the polarization of a propagating laser beam by 90°, ultimately allowing the beam to traverse the laser’s main amplifier four times. A total of six pulse generators is used to support each Pockels cell with its four optical apertures. One-half of a NIF Pockels cell (i.e., two apertures) and its supporting hardware are illustrated in Figure 6.

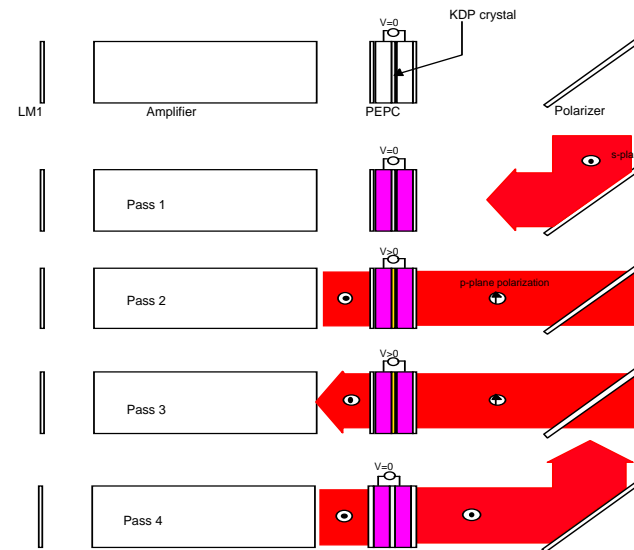


Figure 5. Illustration of PEPC’s function in NIF.

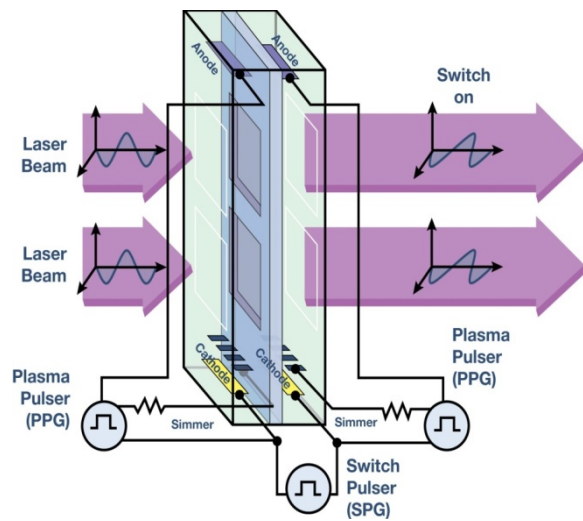


Figure 6. Pulsed power connections for one-half of a NIF PEPC.

D. Subsystem Shot Operations

All three pulsed power subsystems are controlled remotely by the facility's Integrated Computer Control System (ICCS) from the NIF central control room (which also controls all the other subsystems in the facility). At this stage a human operator interacts with/oversees each system on a limited basis during the countdown to a system "shot." However, the vast majority of control is afforded and effected by software and hardware elements of the ICCS. Data acquisition supplemented by automated waveform analysis are keys to monitoring and maintaining the health of the NIF power conditioning subsystems. As such, each shot waveform is monitored and logged, with waveforms failing to meet pre-set standards documented by problem logs.

The three power conditioning subsystems operate only for the last few minutes of a much longer pre-shot countdown sequence. The PEPC begins to operate 280 seconds before the propagation of the laser, pulsing every 5 seconds until the laser has fired. This gives the subsystem time to inject gas, initiate the simmer, apply the plasma and switch pulses with the software monitoring and vetting all signals before the other two power conditioning subsystems "come to life." The PCUs begin their 30-second charge sequence approximately 90 seconds before the laser shot. Once a PCU has charged and begun to regulate, the PCS modules begin to charge. The PCS reaches final voltage only 3–5 seconds before laser propagation to minimize stress on the capacitors in the system. The NIF master timing system issues triggers to each system for appropriate timing relative to the laser shot.

III. COMMISSIONING

A. Vendor Quality Control and Unit Testing

To date, performance of the three subsystems has been

very good. The factors contributing to the performance of the three subsystems are numerous, with many occurring long before the hardware was actually installed in the facility. In particular, a combination of fully prototyped, conservative designs, high-quality vendors and integrators, pre-installation testing of key components (e.g. energy storage capacitors), rigorous quality control, inspection and calibration has contributed to a quality product with good reliability. Each PCS, PCU and PEPC pulser was fully tested at the integrator under realistic operating conditions prior to being shipped to LLNL, where they were re-tested. In addition, lessons learned from laser system operation (beginning with the NIF Early Light campaign in 2002) have been fed back into the designs allowing improvements to be made during the production cycles.

B. Installation Qualification (IQ)

The initial step in placing new hardware in the facility was to perform a complete series of initial tests to verify unit performance and to uncover any incipient problems. As an example, each PCS module was subjected to the following:

- Re-torquing of each high current connection
- Thorough visual inspection of all components
- End-to-end verification of all control, safety and power connections
- Operational verification of each component
- Integrated low-voltage tests

In addition to module tests, the high voltage buses and insulation were subjected to DC hi-potting. Flashlamp loads were inspected and fully tested in an offline facility before being installed and connected to PCS modules.

C. Operations Qualification (OQ)

Before being declared ready for laser operations, each element of the subsystem was subjected to an extensive operations qualification process. This facet of the qualification process verified that the assembly met its requirements under repeated, realistic operating conditions. Depending on the subsystem, testing consisted of tens to hundreds "shots." Note that a "re-OQ" is required whenever a significant repair or upgrade is implemented.

III. OPERATIONAL EXPERIENCE

A. Maintenance/Maintenance Philosophy

Over the last year the three NIF power conditioning subsystems have transitioned from a mode of "filling the building" to one of supporting large numbers of multi-beam shot operations. Hence, there has been a significant effort to ensure that the power conditioning hardware meets NIF standards for high reliability. As intimated, meeting Reliability, Availability and Maintainability (RAM) requirements is particularly important for the power conditioning systems, which come to life only for

the last few seconds to minutes of what are often multi-hour shot cycles. Irregularities and equipment failures at this late stage are particularly expensive in terms of time and manpower (and targets).

Each of the three pulsed power systems employs a line replaceable unit (LRU) philosophy as part of its concept of maintenance and operations. This allows problems/repairs to be addressed in offline facilities while minimizing “downtime” in the facility. Complementary to this has been the development of detailed spares plans and the purchase of sufficient spare components to keep the equipment on line.

It comes as no surprise that the operation of a facility as large and complex as NIF (in general) and the pulsed power systems (specifically) require a high degree of organization so operational issues are not allowed to “fall through the cracks.” Power conditioning repairs (along with those of all other elements of the facility) are driven by two complementary systems: a preventive maintenance tool and a reactive maintenance tool. As implied, the preventive maintenance tool consists of scheduled inspections and maintenance for items whose failure mechanisms and timescales are both predictable and well understood. (An example of this is the main switch in the PCS. Extensive offline testing has shown that refurbishment can be predicted (and therefore scheduled) by tracking Coulomb transfer for each switch.) Reactive maintenance is typically performed on the day shift following the occurrence of an issue. (Carry-over maintenance invokes a restriction that notifies shot operations that equipment is unavailable for shot participation.) Operational problem logs are written by the operators at shot time with the subsystem manager receiving appropriate notification of the problem type along with details of the failure. Operators are aided by “onboard,” real-time diagnostic tools that monitor and archive the status of waveforms, temperatures, etc. Subsystem managers formally review operational data on a monthly basis to ensure that problems are being identified and solved in an expedient and effective manner. Root-cause analysis is performed on recurring problems to determine required upgrades, thus eliminating additional occurrences.

At this point, a less-well-developed aspect of maintenance is the use of “leading indicators.” Ideally, these indicators can be used to schedule maintenance activities during designated maintenance periods rather than having the associated failures occur during shot operations. As an example, each PEPC LRU has an onboard turbo pump to achieve/maintain required low pressures. It is well known that rotor temperature can be used to predict bearing failure. However, the warning period appears to be only 1 to 3 days. A superior measure of bearing health appears to be rotor vibration, as measured by one or more sensitive accelerometers. In addition, we are looking at enhanced analysis that may predict, for example, incipient cable, capacitor and switch

failures.

Finally, we are continuing the process of addressing component life-cycle issues. In some cases, spares have been purchased (or will be purchased) in quantities that will accommodate predicted failure rates for the life of the facility. Other components will receive periodic upgrades to minimize the impact of obsolescence issues that will invariably occur during the life of the three-decade-long project.

B. Worker Training

The need for uniform training and documented experience of workers has led to the development of detailed qualification cards that capture both training requirements and training status for virtually all categories of workers and significant numbers of types of work. This is supplemented and complemented by a laboratory-wide training system that provides monthly updates to workers and their supervisors, giving a 3-month look-ahead for upcoming training.

To first order, workers are divided into two broad categories: operators and maintenance workers. We have found it advantageous to hire workers who have the capabilities to perform both jobs. Both operators and maintenance workers are then sub-divided into basic and advanced level, based on their level of experience, training and understanding. Completion of each level requires months of training and hands-on experience under the tutelage/supervision of qualified workers and engineers. In addition, workers complete a suite of safety training classes including but not limited to electrical safety, high-voltage safety, capacitor safety and lock-out/tag-out (LOTO).

C. Work Planning/Control

Anticipating recent Department of Energy requirements that are currently being implemented across the complex, NIF has for several years required that all work in the facility be permitted (with approval coming through the immediate management chain) and then approved by a centralized work control office. Work control is particularly important as a means of de-conflicting the myriad tasks that occur on a daily basis. All work must be explicitly covered by existing safety documentation in order to be performed.

A fundamental aspect of working the NIF facility is the Safe Plan of Action (SPA), a formalized pre-job brief in which a detailed task list is generated by the team’s responsible individual (RI). The RI also identifies associated hazards and their mitigations. All workers involved in a task participate in a pre-work discussion to make sure everyone is appropriately trained, fit for duty and that they have a good understanding of the activities that are to take place, the potential hazards and the mitigations in place for those hazards.

D. Additional Safety Considerations

The danger associated with high-voltage/high-energy systems leaves no room for error. As such, detailed energy isolation plans have been developed for the three pulsed power systems. In a nutshell, these plans provide step-by-step checklists and protocols for LOTO, zero energy checks and “safing.” The lattermost term refers to verification of dump relay status, inspections that ensure dump and bleeder resistors are intact, voltage (re)checks, capacitance checks, installation of ground hooks/ground sets and the posting of status signs on equipment. Specially trained and qualified “energy owners” also add to the process by bringing a more global knowledge of the system and when it may be logically and safely shut down/re-energized.

E. RAM Details

The three subsystems have performed extremely well during laser operations. Since August 2008, when the last of the PCS modules was qualified, PEPC and PCS have displayed ~95% availability, with PCU approaching 100% availability for the equivalent of 450 192-beam rod (i.e., relatively low energy) shots and 29 192-beam system (very high energy) shots. From a reliability standpoint, none of the subsystems has forced the repeat of a completed shot, thus achieving a reliability of 100% by NIF’s RAM definition. See Table 1 for details.

Table 1. Power Conditioning Availability and Reliability for August 2008 through June 2009.

Subsystem	Availability		Reliability	
	Goal	Current	Goal	Current
PCU	99.995%	99.87%	99.966%	100%
PEPC	99.680%	94.68%	99.410%	100%
PCS	99.940%	95.08%	92.010%	100%

While performance has been extremely positive, we are making every effort to improve the subsystems so they meet or exceed the very aggressive goals enumerated in Table 1. In particular, we are taking advantage of periodic offline operation of the hardware, scheduled testing and recalibration, extensive use of automated software monitoring of hardware performance during shot operations (with particular emphasis on detecting slightly degraded performance that often signals the onset of larger problems), detailed problem logging and root cause analysis along with regimented re-qualification following repairs and/or upgrades. As we better understand the subsystems we are also implementing preventive maintenance processes.

Failures for the pulsed power subsystems can be “binned” into two broad categories: hardware and software, with each being responsible for approximately half of the problems encountered. Interestingly enough, the majority of hardware failures have not been in the high-voltage/high-power side of the equipment (e.g., there have been no capacitor failures in PCS) but rather in the

low-voltage/control portions of the systems, though there is some evidence of pulsed-power-generated noise contributing to some fraction (though certainly not all) of the problems. Software-induced problems in turn can be characterized as falling in one or more of several categories: poorly documented requirements; “brittle” software resulting from overly-strict or difficult-to-implement requirements; or difficulties in integrating subsystem software into the larger multi-million-line facility shot-cycle software.

IV. FUTURE WORK

NIF is designed as a “target shooter” with a near-term goal of achieving ignition on a laboratory scale with long term goals of providing extensive data for stockpile stewardship, fusion energy and astrophysics studies over the next thirty years. This will happen only with reliable support from the three pulsed power subsystems. Thus, a key near-term task is to continue to exercise the systems to identify any and all deficiencies in the three subsystems and address their root causes so that they will meet and exceed all performance requirements. Understanding leading indicators will be keys to developing maintenance schemes that rely primarily on preventive/scheduled maintenance rather than reactive maintenance. In addition, components will receive periodic upgrades to minimize the impact of obsolescence issues that will invariably occur during the life of a three-decade-long project. Finally, systems will be upgraded as required to support future missions of the facility, including Advanced Radiographic Capability.⁴

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